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IMPROVED METRICS FOR PERSONNEL VULNERABILITY ANALYSIS

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MAY 1991

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Traditional methods used for quantitative analysis of penetrating injuries is explained and criticized. Potential improvements to the methods are proposed.

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1. Introduction

Recent work on the general military system vulnerability problem[1] has proven the usefulness of clearly distinguishing between four "Spaces" of vulnerability. In this paper, the four-space conceptual model will be brought to bear on the important special case of personnel vulnerability.* This approach will permit illumination of the following issues:

- Traditional modeling practice in the personnel vulnerability area.
- Similarities and differences between traditional practices in materiel system vulnerability analysis and personnel vulnerability analysis.
- Technical problems with traditional modeling practice.
- The inadequacy of traditional practice for applications such as Live Fire Testing.
- The possibility of an improved modeling practice which is free from the major technical difficulties infecting traditional practice.

It is not the aim here to present detailed methods of calculation which can be obtained elsewhere.[2] The goal is rather to take a fresh perspective on the overall problem. Thus the paper will be primarily *expository* and *critical* with respect to traditional practice; it will be primarily *programmatic* with respect to envisioned improvements.

2. Traditional Personnel Vulnerability Modeling

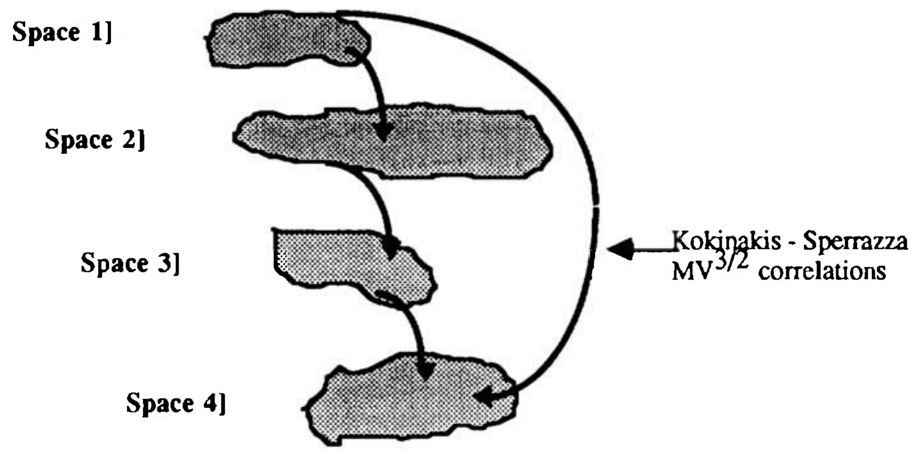
The four-space model for penetrating injuries is shown in Figure 1. **Space 1]** describes the potential encounters between a penetrating threat and a human target. We say that each set of **Space 1]** encounter conditions is *mapped* into **Space 2]**; this contains details of component damage. These details are typically in terms of wound tracts along which the damage to specific tissue types is characterized by hole size. This mapping could be obtained by either shooting the relevant projectile at living tissue and recording the result or by a mathematical model such as BRL's ComputerMan.[3] Present practice dictates that the penetration (as a function of tissue type) information required by a model like ComputerMan is taken from shots against living tissue or is estimated from shots against gelatin. This penetration information permits us to calculate fundamental component damage which for personnel vulnerability is damage against key organs. It is perhaps worth pointing out that there is an important asymmetry in the form of the **Space 2]** damage states between materiel and personnel targets. For materiel targets it is customarily assumed that after an encounter with a damage mechanism each component may be adequately

1. Paul H. Deitz, Michael W. Starks, Jill H. Smith and Aivars Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment (U)*, Ballistic Research Laboratory Memorandum Report BRL-MR-3880, November 1990.

*Throughout the paper, "personnel vulnerability" refers solely to penetrating mechanisms such as fragments, bullets, and flechettes.

2. David N. Neades, Russell N. Prather, *The Modeling and Application of Small Arms Wound Ballistics*, Ballistic Research Laboratory Memorandum Report, (in press), and the very extensive references contained therein.

3. Richard Saucier, *ComputerMan User's Manual (U)*, Ballistic Research Laboratory Technical Report BRL-TR-3141, August 1990.



1. Warhead/Target Interaction ⟶
   (mass, velocity, shape, material composition, entry location of hit on body)
2. Component Damage State ⟶
   (penetration; biotrauma in terms of tissue damage; not binary)
3. Measures of Performance ⟶
   (Functional Group: degree of functionality of arms and legs)
4. Measures of Effectiveness
   (Incapacitation; "P(I/H)" for various tactical roles)

Figure 1. Conceptual Spaces of Vulnerability Modeling Applied to Traditional Modeling of Penetrating Injury.

characterized as either "dead" or "alive".[4] For mechanical components which have a single function the assumption appears to be plausible. For personnel targets, on the other hand, the component damage is *not* regarded as binary; rather it is binned by hole size in the components (i.e. body parts) encountered.

The mapping from **Space 2]** component damage into a **Space 3]** measure of performance is accomplished in the same way whether **Space 2]** has been calculated in a model or measured in a live fire test. The mapping is accomplished by means of a so-called Functional Group* table; a portion of such a table for the muscular system is shown in Table 1. For each component/hole-size combination a Functional Group is assigned for each of six time periods ranging from 30 seconds to five days. The Functional Group itself indicates for each of the four limbs whether the limb is fully functional, totally dysfunctional, or partially functional. These Functional Group assignments were made by medical assessors associated with the live animal testing conducted at

1. See the Appendix to my "*Assessing the Accuracy of Vulnerability Models by Comparison with Vulnerability Experiments*," Ballistic Research Laboratory, BRL-TR-3018, July 1989, for an argument that this assumption does not do violence to the facts.

*There have been a variety of Functional Group tables developed over the years, ranging in size from 10-81 Groups. The assignment of a particular number to a limb state is in a sense arbitrary; the table can actually be regarded as showing limb function as it varies with wound tract.

TISSUE NAME	HOLE SIZE DIAMETER (mm)	LIMB STATE AT POST-WOUNDING TIMES 30sec	5min	30min	12hrs	24hrs	5days
		(Order: LArm RArm LLeg RLeg)					
Muscle (head&neck)	31	NFNN	FFFF	FFFF	FFFF	FFFF	FFFF
	23	NFNN	NFNN	NFNN	NFNN	NFNN	NFNN
Muscle (thorax)	31	NFNN	NFNN	FFFF	FFFF	FFFF	FFFF
	23	NFNN	NFNN	NFNN	NFNN	NFNN	NFNN
Muscle (abdomen)	31	NNNN	NNNN	FFFF	FFFF	FFFF	FFFF
	23	NNNN	NNNN	NNNF	NNNF	NNNF	NNNF
Muscle (pelvis)	17	NNNN	NNNN	FFFF	FFFF	FFFF	FFFF
Muscle (upper arm)	29	NTNN	NTNN	NTNN	NTNN	NTNN	NTNN
	21	NFNN	NFNN	NFNN	NFNN	NFNN	NFNN
Muscle (forearm)	29	NTNN	NTNN	NTNN	NTNN	NTNN	NTNN
	21	NFNN	NFNN	NFNN	NFNN	NFNN	NFNN
	1	NNNN	NNNN	NNNN	NNNN	NNNN	NNNN
Muscle (wrist)	29	NTNN	NTNN	NTNN	NTNN	NTNN	NTNN
	21	NFNN	NFNN	NFNN	NFNN	NFNN	NFNN
Muscle (upper leg)	34	NNNF	NNNF	NNNF	FFFF	FFFF	FFFF
	17	NNNF	NNNF	NNNF	NNNF	NNNF	NNNF
Muscle (lower leg)	34	NNNF	NNNF	NNNF	FFFF	FFFF	FFFF
	17	NNNF	NNNF	NNNF	NNNF	NNNF	NNNF
Muscle (foot)	34	NNNF	NNNF	NNNF	FFFF	FFFF	FFFF
	17	NNNF	NNNF	NNNF	NNNF	NNNF	NNNF

N - No effect upon use of the limb

F - Loss of fine muscle control or weakness

T - Total loss of function of the limb

Table 1. Muscular System Limb States

Edgewood Arsenal during the 1950s and 1960s. Unfortunately, full details of the ground rules under which these medical assessments were conducted were not published, and are now irrecoverable. This absence of a clearly articulated rationale has from time to time put the Army in an intellectually weak position when the traditional personnel vulnerability methodology or quantitative estimates made using it have been criticized. The Functional Group Tables can be criticized as "too high" or "too low", and the absence of a clear audit trail has made it difficult for the Army to generate an intellectually compelling response.

Mapping from a **Space 3]** Functional Group into a **Space 4]** Measure of Effectiveness (MOE) is accomplished by means of Table 2.[5]

Each Arm	Each Leg*	Functional Group	Percent Disability Assault	Percent Disability Defense	Percent Disability Reserve	Percent Disability Supply
N,N	N,N	I	0	0	0	0
N,N	N,F	II	50	25	75	25
N,N	F,F	III	75	25	100	50
N,N	N,T	IV	100	50	100	100
N,N	T,T	V	100	50	100	100
N,F	N,N	VI	50	25	75	25
F,F	N,N	VII	75	50	100	50
N,T	N,N	VIII	75	75	100	75
T,T	N,N	IX	100	100	100	100
F,F	F,F	X	75	75	100	75
F,F	F,T	XI	100	75	100	100
F,F	T,T	XII	100	75	100	100
F,T	F,F	XIII	100	100	100	100
T,T	T,T	XIV	100	100	100	100
N,N	F,T	XV	100	50	100	100
N,F	F,F	XVI	75	50	100	75

Codes - N No effect
F Loss of fine muscular coordination
T Total loss of extremity function
*** No attempt is made to differentiate between the right and left limbs.**

TABLE 2. Percent Disability Vs. Functional Group for Four Tactical Situations

As the Table indicates, the chosen **Space 4]** MOE is percent disability for four different tactical roles. There are at least three kinds of difficulties with the **Space 3]** to **Space 4]** mapping as traditionally conceived.

One problem concerns the detailed provenance of the postulated relations between Functional Groups and the ability to execute military tasks. In the paper just cited, Mr. Kokinakis and Dr. Sperrazza say that the estimates "are based on a consensus of opinion of medical assessors and of combat personnel". They provide a brief discussion in an appendix which covers some of the assumptions concerning the four tactical roles; however, there is no adequately documented

5. William Kokinakis and Joseph Sperrazza, *Criteria for Incapacitating Soldiers with Fragments and Flechettes*, Ballistic Research Laboratory Report, BRL-R-1269, January 1965.

account of precisely how Table 2 was generated or of the limitations inherent in the methods used. Kokinakis and Sperrazza assert that the approach used provided "best estimates", but it is far from clear precisely what that means. A more robust audit trail for our **Space 4**] metrics is clearly required.

Related to the problem of unclear provenance is the problem of vintage. The percent disability estimates were developed for the four tactical roles as conceived of in the 1950's. There is every reason to expect that as doctrine has evolved over the past forty years towards much more highly mobile forms of manuever warfare, the limb requirements for the various tactical roles have changed. So even if the intellectual grounds for Table 2 were impeccable, it would still be dubious for use in analysis of 1990's issues.

A second set of technical problems with Table 2 concerns its adequacy in clarifying the problems it was designed to address. Many important military tasks critically depend on the abilities of speech, hearing, and vision. Such abilities do not readily yield to analysis in terms of limb function. The limited extent to which the traditional modeling methods can be used to illuminate such abilities has long been recognized as a significant data void.

Before turning to the third problem, it is important to emphasize that it will be seen as having much broader practical consequences for the Army's personnel vulnerability program. The **Space 2**], **Space 3**], and **Space 4**] difficulties enumerated thus far have to do with the lack of detailed rationale and audit trail for the Table 1 and Table 2 mappings. In principle, the difficulties could be addressed by obtaining appropriate medical/physiological review of the **Space 3**] Functional Group mappings and analogous review or revision of the **Space 4**] tactical role mappings. Such reviews might or might not result in detailed changes to the Table 1 and Table 2 mappings, but definitely would result in a clearer account than is now available of the methodological assumptions and limitations inherent in the data, and of a fuller explanation of the data points themselves.

The problem I turn to now would remain even if all data of the type in Tables 1 and 2 were fully "validated"; it concerns the *form* of the **Space 4**] metric. As will be shown below, the traditional **Space 4**] metrics invite mathematical error. If the **Space 4**] metrics are *formally* flawed, then the traditional method cannot be defended as intellectually adequate by merely validating the underlying databases.

This third problem seems at first to be merely terminological, although on deeper inspection the difficulty can be seen as more serious. Traditional practice has been to calculate various averages over the percent incapacitation values shown in Table 2 and to call the resultant averages probability of incapacitation given a hit. Kokinakis and Sperrazza use this formulation to define what they call P_{hk} and then (correctly) add: "The term probability of incapacitation is a misnomer here. Actually what is derived is an estimate of an ***average level*** of ***incapacitation***."

At first blush, it may be difficult to understand why our distinguished authors would intentionally perpetuate "misnomer" terminology for the central quantitative concept of their paper. They make it explicitly clear that what is being calculated is an average level of incapacitation, and their "misnomer" remark shows they were patently aware that the calculated quantity cannot be arbitrarily changed to a probability by fiat. Yet their terminology encourages just such an arbitrary change.

Although speculation concerning motives is not without dangers, I suspect that our authors winked at the terminological equivocation for something like the following reasons. Even by 1965,

the P_{hk} terminology had become bureaucratically entrenched. Moreover, the calculated quantities had proven useful for illuminating the intended set of issues concerning relative injuring power. Finally, there were established systems analysis uses for personnel vulnerability estimates which required probabilistic input. Reasons of the kind given may psychologically explain the equivocation, but they do not justify it.

The terminological mistake made here by Kokinakis and Sperrazza is very similar to one made by early materiel target vulnerability analysts who relied on a **Space 2]** to **Space 4]** mapping called the Standard Damage Assessment List. The numbers in these lists, and in Table 2, are actually fractional losses of function; it is more than a semantical infelicity to simply assert that these losses of function are probabilities.[6] Consider Table 3 and the associated argument.

1985 - .02
1986 - .03
1987 - .03
1988 - .02
1989 - .04
1990 - .04
1991 - .03 (projected)

Table 3. Fraction of Starks Income Spent on Wine

Now it might be reasonable to conclude from Table 3, especially in the absence of additional information, that Starks will probably use about 3% of his fractional fiscal capability for 1992 on wine. This would embody a perfectly normal form of scientific inference. However, we *cannot* conclude from the Table that the probability that Starks will spend his entire income on wine is .03. Unfortunately, it is precisely such an interpretation which the P_{hk} or $P(I/H)$ terminology suggests and even requires.

The difficulty is serious because downstream users of personnel vulnerability estimates really do require probabilities for many of their applications; such users have been too easily tempted to accept the suggestion implicit in the terminology and to use average incapacitation estimates as probabilities of complete incapacitation. To summarize this part of the discussion: three serious problems with the **Space 3]** to **Space 4]** mapping have been identified. One concerns the absence of rationale and audit trail for the mapping function itself, i.e. Table 2. The second problem concerns the technical adequacy of Table 2. Finally, the third problem concerns the form of the **Space 4]** metric. I will return to proposed solutions for these issues below. For completeness, though, let us first finish the discussion of Figure 1.

The exposition thus far has gone through the Spaces of vulnerability modeling step-by-step, just as is done in the ComputerMan Model. There is also a more expedient route to obtaining personnel vulnerability estimates. This is shown in Figure 1 as a **Space 1]** to **Space 4]** mapping via the Kokinakis-Sperrazza $MV^{3/2}$ correlations.* In their paper cited earlier, they take the **Space 4]**

6. Michael W. Starks, *New Foundations for Tank Vulnerability Analysis*, **The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association**, Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988. The emphasis in this paper is on average loss of function versus probability of no function issues for the anti-armor case.

*Other correlations have been proposed as well where the Space 1] variable is kinetic energy or its rate of change.

percent disability MOEs derived from the detailed process and fit them to a function of the **Space 1]** variables mass and velocity. This functional form has been used within the Defense Department for many years, and it must be acknowledged that it has the virtue of simplicity.

However, there are a number of problems with the **Space 1]** to **Space 4]** mapping; some obvious and some less so. The obvious problems are that the three central difficulties with the detailed procedure described above are clearly, if implicitly, inherited by any simplified route to the same numerical conclusion. There are more subtle technical difficulties as well which will only be briefly mentioned here. One issue is the fact that in the detailed model such factors as velocity retardation as a function of tissue type have been refined and improved over the years. However, the regression has not been systematically redone so that there is an inconsistency of unknown magnitude between the detailed and regression methods. A second issue concerns the quality of the $MV^{3/2}$ regression itself. Although Kokinakis and Sperrazza say that "on the average" the form yielded a good fit, they neglected to provide any of the customary quantitative indicators of goodness. In an earlier paper[7] Allen and Sperrazza provide limited rationale for the form of the regression, but as they acknowledge, their arguments are far from conclusive.

3. Personnel Vulnerability in Live Fire Testing

Consider an idealized Live Fire Test (LFT) event, taken as providing confirmatory or refuting evidence for the theories or models which are customarily used to deduce relevant observable outcomes. Suppose we are firing a large kinetic energy penetrator against a tank which has four soldiers as crew members. We have models to predict tank vulnerability and personnel vulnerability for such events. To confirm/refute our tank vulnerability model we can assess which vehicle critical components are dysfunctional ("killed") in the test event. This set of components can then be compared to the set calculated by our model and appropriate statistical conclusions can be drawn concerning model acceptance or rejection.

In our thought experiment we can provide an analogous set of steps for personnel vulnerability modeling. In the test, we could assess for each crew member the type and extent of damage to organs and other body parts (**Space 2]**). Further, we could subject each injured crew member to additional tests to obtain objective measures of limb function (**Space 3]**) as it varies with time or of performance (**Space 4]**) to determine which tasks can and cannot be accomplished. The experimental outcomes thus measured -- whether organ damage in **Space 2]**, limb function in **Space 3]**, or task performance in **Space 4]** -- could then be compared with model outcomes.

Now the process of theory-experiment comparison just described can actually be, and is in practice, conducted for materiel system vulnerability. For materiel systems the proper focus for theory-experiment comparison has been found to be the **Space 2]** damage vectors. Briefly, the reason for this is that **Space 4]** agreement can easily mask significant disagreement between the measured and calculated damage vectors of **Space 2]***. From a mathematical point of view, the situation is similar for personnel vulnerability. A **Space 4]** $P(I/H) = .5$ could be mapped from any number of **Space 3]** Functional Groups which in turn could be mapped from any number of **Space 2]** damaged body components. So for reasons analogous to those for materiel targets, **Space 2]** is the appropriate level at which to compare theory and experiment.

For ethical reasons, Live Fire Tests are not configured with living humans at crew stations. Thus we are not in a position to measure penetration and hole sizes in body parts when we conduct such tests; nor can we compare those outcomes with those generated by ComputerMan.

7. F. Allen and J. Sperrazza, *New Casualty Criteria for Wounding by Fragments*, Ballistic Research Laboratory Technical Report, BRL-TR-996, October 1956.

* See the paper cited in footnote 4 for the detailed argument.

What we do measure is mass, velocity, and orientation of potentially penetrating projectiles, and then use those as input to our further modeling; this could either be through the detailed method (ComputerMan) or through the **Space 1]** to **Space 4]** regression discussed above.

The fact that it is consequently very difficult to confront our personnel vulnerability models with potentially refuting "critical experiments" is a direct result of our inability to include live animals in Live Fire Tests. We are slaved to the animal testing conducted at Edgewood in the 1950's and 1960's, and to our hope that retardation and body component damage was carefully reduced, recorded, and embedded in ComputerMan. Our current **Space 1]** to **Space 2]** mapping is only as good as this database. This mapping is testable in principle, but cannot be realistically tested in practice under current DoD guidelines.

As was suggested above, it is not clear that the traditional mapping from **Space 3]** to **Space 4]** measures of incapacitation is testable even in principle. This is due to the uncertainties involved in determining precisely what tasks are required by the four tactical roles in Table 2. A further point relevant to personnel vulnerability aspects of Live Fire Testing concerns the nature of the **Space 4]** metrics themselves. As was explained above, despite the terminology of P_{hk} or P(I/H) the metrics of **Space 4]** are intended as *average* values of incapacitation for the various tactical roles. Suppose we are asked to predict personnel incapacitation for a specific Live Fire Test configuration, say a TOW missile fired from a certain azimuth at a tank with four crew members. The most useful form of personnel vulnerability prediction would be that which indicates, for each crew member, whether or not he can do his job. This indication could be either binary or probabilistic. If the prediction were binary, it might take the form:

- After the TOW impact on the tank, the driver will not be able to do his job.

If the prediction were probabilistic, it might read:

- After the TOW impact on the tank, the probability is .7 that the driver will not be able to do his job.

Given that LFT personnel vulnerability predictions were made in either of the above forms, we would be well positioned to make specific predictions concerning the remaining combat capability of the tank. For example, if no hardware components are killed affecting mobility, then the immediate ability of the tank to move will be a function of whether there are surviving crew members able to drive.

The calculational scheme just described is quite different from the manner in which the traditional Figure 1 methods have been brought to bear on LFT predictions. What would typically be done for the TOW versus tank situation is as follows. Plywood manikins would be placed at the crew positions. After the shot, masses and velocities of penetrating fragments would be inferred from the holes in the manikins. In turn, the masses and velocities would be used in the **Space 1]** to **Space 4]** $MV^{3/2}$ correlations to infer average value of incapacitation for the assault role.

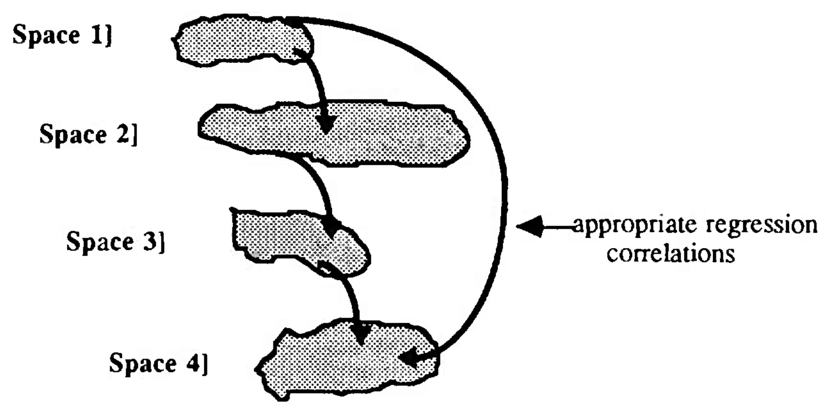
I hope it is evident that the traditional LFT prediction scheme is seriously deficient in several ways. For one thing, it is not clear that assault role criteria are appropriate for application to armored vehicle crews. Unfortunately, under the traditional modeling scheme the assault criterion is the closest **Space 4]** metric available. A second deficiency is that *average* incapacitation for the LFT initial conditions is of no help in accurately determining what the predicted outcome should be for the *specific conditions* under test. To be of maximum use for illuminating LFT events, our **Space 4]** personnel vulnerability MOE must be probabilistic in nature.

4. Interim Summary

There is a coherent mapping across four Spaces of Vulnerability which results in MOEs having to do with human incapacitation. Unfortunately, these MOEs have traditionally been called probabilities when they are not. Even more unfortunately, downstream users of personnel vulnerability estimates require probabilistic estimates, which has often meant they simply used average incapacitation estimates as probabilities. The specific rationale for the **Space 2**] to **Space 3**] mapping is not available. Moreover, the **Space 3**] to **Space 4**] mapping (Table 2) does not appear intellectually defensible, even on its own terms. Finally, the **Space 4**] metrics, if used as intended, do not provide the right form of answer to support Live Fire Test predictions.* Can we move away from some of these difficulties?

5. Revised Method for Personnel Vulnerability Calculations

A conceptually clearer and far more informative set of **Space 3**] and **Space 4**] metrics could and should be developed which are free from the difficulties I have described as inherent in the traditional mapping process. Proposed improvements will be explained in the context of a revised mapping procedure shown in Figure 2.



1. Warhead/Target Interaction →
   (mass, velocity, shape, material composition, entry location of hit on body)
2. Component Damage State →
   (penetration; biotrauma in terms of tissue damage; not binary)
3. Measures of Performance →
   (ability to perform atomic tasks (see, walk, run, etc)
4. Measures of Effectiveness
   (P(I/H) for various roles defined as Boolean functions over atomic tasks)

Figure 2. Conceptual Spaces of Vulnerability Modeling Applied to Proposed Modeling of Penetrating Injury

*Even with an appropriate form of Space 4] MOE there remains the general problem of validating a model with a distributional outcome by use of single test events.

The present time is particularly propitious for developing improved metrics. Over the past few years, the traditional methods have come under increasing scrutiny and criticism. This has led to a Department of the Army requirement for BRL to "validate" its wound ballistics data base by having medical assessors review the entire modeling process with special attention to the **Space 2]** to **Space 3]** and **Space 3]** to **Space 4]** mappings. Early interaction with the Army medical community has demonstrated that successful completion of this validation process will be time-consuming, difficult, and expensive. Rather than spending taxpayer funds in a "validation" effort of a methodology which is inherently flawed, it appears prudent to direct those monies towards development of an analytical scheme which possesses greater intellectual coherence.

Central to the improved procedure is abandonment of the notion of Functional Group as the essential **Space 3]** performance measure. As was made clear above, the mappings into traditional **Space 3]** Functional Groups suffer from poorly documented provenance; moreover, the F (loss of fine muscle control) category is inherently vague when applied to specific military tasks. In addition, specification of limb function provides absolutely no clarification of a person's ability or inability to perform essential military tasks requiring vision, speech, or hearing. It deserves emphasis that dropping the traditional **Space 3]** limb function metrics in no way involves loss of information from the animal experimentation conducted at Edgewood in the 50's and 60's. The key information from this series of experiments is in **Space 1]** and **Space 2]**. It includes retardation and hole size for a variety of projectiles. This is the information that must be preserved, and it is under the revised model of Figure 2. The relative independence of the **Space 1]** and **Space 2]** input information from the **Space 3]** and **Space 4]** output metrics was clearly acknowledged by the original Edgewood investigators. As Gould[9] and colleagues point out in one of the seminal papers:

> In this entire study, extremity function has been used as the common end point for disability, following experimental missile trauma. Evaluation was made almost on a purely pathological-anatomical or physiological derangement basis, in respect to extremity dysfunction.

In short, the limb function assessments were based primarily on anatomical and physiological analysis of wound tracts, and were not based on observed limb function of the experimental animals.

The improved procedure would replace the Functional Group Tables like those of Table 2 with Tables directly mapping tissue/hole size information into a time functional series of matrices indicating whether or not certain "atomic tasks" could be performed. An extract of what a new mapping into **Space 3]** might look like is shown in Table 4.

Circulatory System	Hole Size (mm)	See	Hear	Talk	Walk	Run	Lift	Aim	Shoot	Drive
Heart (Chambers)	5	0	0	0	0	0	0	0	0	0
	3	.	.	.	.	.	.	.	.	.
		.	.	.	.	.	.	.	.	.
	2	.	.	.	.	.	.	.	.	.
	1	1	1	1	1	1	1	1	1	1

Table 4. ATOMIC TASK CAPABILITY (30 Seconds After Injury)

9. Robert A. Gould, Milford A. Vaughn and Elmer G. Worthley, *Wound Ballistics of the 16 Grain Steel Preformed Fragment*, Chemical Corps Medical Laboratories Research Report, MLR-R-393, August 1955.

A modified version of the improved procedure would be to have appropriate experts associate an existing trauma scoring system such as the Abrreviated Injury Scale (AIS) with the capability for atomic task performance. This strategy might allow us to *improve* our predictive capability over time by use of data collected from trauma centers and hospital emergency rooms.

Let us turn to some of the difficulties that we can expect to encounter in developing new **Space 3]** tables. First, it must be acknowledged that developing estimates of atomic task performance capability requires that subjective physiological judgments be made by appropriate experts. I note that this was also true for the mapping into Functional Groups which constitutes the traditional **Space 2]** to **Space 3]** mapping, and that the resources required to validate and provide an audit trail for the traditional mapping are not clearly distinct from those required to generate a Table 4 style mapping in the manner indicated above. If we are going to expend a substantial sum on development of this mapping, why not develop one that is free of the conceptual problems noted above and is clearer and more explicit concerning task performance?

Second, it must be acknowledged that the list of "atomic tasks" as proposed in Table 4 is merely provisional, and that substantive effort will be required to articulate a list which inherently must satisfy a number of partially conflicting conditions. This list must be rich enough to support subsequent **Space 4]** metrics concerned with a wide variety of different military roles. However, each task in the list must be explainable with sufficient specificity to allow expert physiologists to fill in hundreds of Table 4 type entries while minimizing the requirement for subjective judgments. This will be a difficult task, but it is not clearly more difficult than assignment or validation of Functional Groups.

A third issue requiring resolution for an improved **Space 2]** to **Space 3]** mapping is the precise nature of the **Space 3]** metrics themselves. In Table 4 one finds zeroes and ones, reflecting an assumption that for a given wound, the probability of successful accomplishment of the atomic tasks is binary. It seems plausible for a specifically defined wound tract in a given individual coupled with an atomic task defined in sufficient detail that the outcome really is binary -- the individual can accomplish the task or he can't. However, what is needed for personnel vulnerability is not an estimate for this or that soldier but for a population of soldiers. Under this assumption the entries in Table 4 should be probabilities of successful atomic task accomplishment, estimated by experts in physiology as the relative frequency of soldiers who would be able to accomplish the task, given a specified **Space 2]** injury. It seems plausible that for many types of **Space 2]** wound tracts the population variance would be zero with respect to atomic task performance. Tracts involving large holes in the brain would be an example. Presumably 100% of such individuals would be unable to accomplish any atomic tasks so the Table 4 type data really would be binary. For lesser injuries, the population variance might be quite large so the Table 4 entries would have to be in the form of non-binary relative frequencies. Clearly, additional physiological work will be required to determine the optimum form for the mappings into atomic task capability.

Provisionally accept that the three problems just discussed can be resolved in a satisfactory way, and that we can successfully implement a program that yields new **Space 3]** metrics in the form of probability of successful accomplishment of atomic tasks. If the list of **Space 3]** atomic tasks is chosen intelligently, it should be mathematically straightforward to define various military roles in terms of Boolean combinations of the atomic tasks. If any military role can be defined in terms of "ands" and "ors" over a subset of the atomic tasks, then it would be easy to calculate P(I/H) -- probability of incapacitation for that role given a hit -- for a specific wound tract. Well-known extensions would also permit us to calculate various average $\langle P(I/H) \rangle$ values over body regions, about aimpoints, etc. Notice that the improved Figure 2 scheme overcomes the terminology problem discussed above, namely; the use of "P(I/H)" to denote what was in fact an average value of incapacitation. In the proposed mapping, we wind up with a **Space 4]** metric that is in the correct probabilistic form for downstream users of personnel vulnerability estimates.

6. SUMMARY AND CONCLUSIONS

Traditional personnel vulnerability modeling (Figure 1) has been described and some of its limitations noted. Inherent limitations of any personnel vulnerability modeling scheme which has no recourse to animal testing are also noted. A revised personnel vulnerability modeling strategy (Figure 2) has been described which is free from many of the defects of the traditional scheme. BRL will direct part of its mission program in personnel vulnerability to further exploration and development of the improved scheme.

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